Gondwana Research 4 (2) 184-186 (2001) Talk given at **IGCP 368 Workshop on 'Tectonics and mineralization in the Arabian Shield and its extensions.' March 17-25, 2001, King Abdulaziz University, Jeddah, Saudi Arabia.**

Two breeds of ophiolite; their differing origins and contrasting plate tectonic significance, Archaean to Cenozoic.

Miles F. Osmaston *The White Cottage, Sendmarsh, Ripley, Woking, Surrey GU23 6JT, UK.*
e-mail:- miles@osmaston.demon.co.uk

Enthusiasm for investigating ophiolites owes much to the general belief (e.g. Peters et al., 1991), inherent in the Geotimes (Anonymous, 1972) definition of 'ophiolite', that they represent on-land opportunities to study what goes on at mid-ocean ridges (MORs), all being thought to have attained their supracrustal or upper-crustal positions by some variant of the subduction process, referred to (somewhat vaguely) as 'obduction'. Consequently, ophiolite emplacement ages have been regarded as defining times of plate convergence and occurrences have been equated with the positions of plate tectonic sutures. Osmaston (1980; 1995a), however, has stressed that hot-emplaced ophiolites (HEOs - which include most of the best-preserved ones and were the basis of the Geotimes definition) present special problems of generation and emplacement, so should be seen as a separate breed from those structurally 'emplaced' cold (CEOs), such as the Coast Range Ophiolite of California, uplifted into view by the exhuming HP/LT Franciscan Complex.

Studies (Osmaston, 1992; 1994; 1999a) of the subduction downbend process and of the associated often-rapid and extensive tectonic undercutting ('STE'; Osmaston, 1994) of margins and their subsequent imbrication have shown that most subduction zones actually start in an intra-oceanic setting, eventually arriving at continental margins by repeated cycles of STE and imbrication. The resulting ocean-crusted forearcs are evident in the upturned ophiolite slices at the rear of accretionary prisms like those of the Nicoya Complex (Costa Rica), and Makhran (Iran-Pakistan). The Ligurian ophiolites, northern Italy, seem to be a related example. These are seen as examples of CEOs; they have not been 'obducted' or accreted, but simply raised into view by imbrication and by accretion up-front, so they would not precisely mark a future suture. Pursuing these results into the Archaean (Osmaston, 1999b; 2000a) shows that greenstone belts are probably of a similar nature, but exhibit only the uppermost part of the original oceanic crust, the rest having been removed by very shallow STE beneath the forearc. In this case, the halting of subduction, e.g. by the arrival of a microcraton, followed by melting of the underlying subducted oceanic crust by the heat within the subducted plate, provides a suitable source of heat and material for their widespread intrusion by TTG granitoids.

As thus defined, CEOs are found mostly to lack a mantle component and sheeted dykes are scarce. If formed close to a continental margin, studies in the Gulf of California shows that sedimentation greatly modifies the MOR process (Klitgord et al., 1974; and DSDP Leg 63). So it is not surprising that Bickle and Nisbet (1994) failed to recognize Archaean greenstone belts as oceanic crust, as defined in 1972. CEOs also turn up in HP/LT metamorphic belts, interpretable as ex-forearc slices, subducted and lodged across a distant subduction downbend previously cut into the hanging-wall by STE (e.g. the Piemont ophiolites of the Alps; Osmaston, 1997); when exhumed, they can be hundreds of kilometres from the related upper-crust suture.

HEOs, by contrast, are characteristically dominated by a major thickness (e.g. 5km) and sometimes huge extent (400 x 80km in Oman) of mantle tectonite below a supposedly MOR-like crustal section with a highly disrupted base, and emplaced supracrustally at over 1000ºC, as evidenced by contact metamorphic temperatures in the sole. Overall actual slice thicknesses nowhere exceed ~8km, including (where preserved) pristine pillow lavas at the top. Yet, despite the temperature, a number of tectonites exhibit unre-equilibrated high-pressure evidence (e.g. garnet lherzolite, thin picritic melt veins) corresponding to 60km depth or more; and the mafic, always upper, part of the soles exhibit metamorphic pressures of 17-45km depth. A table of these features will be presented. The inescapable conclusion is that the mantle tectonite is not all-of-a-piece with the crustal section, as the MOR interpretation of HEOs would require, but was an exceedingly rapidly rising, partially melted, mantle diapir juxtaposed beneath the crustal section of the same age. Shear-induced segregation of melt at depth, which crystallized on the way up, could then explain the HP mafic part of the sole. Other shear-induced segregations occur as now-residual chromite-dunite pods in many mantle tectonites.

A second feature of many HEOs is that they exhibit lavas and dykes with subduction-related types of composition. In Oman these so-called SSZ (supra-subduction zone) compositions are intruded into and through a MORB-type crust; in the Mirdita (Albanian) and Zambales (Philippines) ophiolites they change across strike from one to the other; in many others only the SSZ compositions are seen. In Oman the age-gap between the two is extremely small, creating a major problem of how to change the setting so rapidly.

As a background to the model proposed below for the genesis and emplacement of HEOs we divert briefly to recent work (Osmaston, 1995b; 2000b) reassessing the MOR process. This work was, in the first place, driven by the recognition that extensive STE and the resulting 'flat-slab' subduction interface profiles, indicates the presence of young-plate thermal buoyancy. This implies that when constructed at MORs the resulting plate should incorporate a substantial thickness of LVZ (low-velocity zone) material, with its heat content, as an integral part of the plate. Recognition (e.g. Hirth and Kohlstedt, 1996) that the interstitial melt in the LVZ will capture the water-weakening of the mineral structure and make it very stiff has made possible an MOR model with a deep, narrow (20cm?) axial mantle crack, passing through at least the upper part of the LVZ. The crack-width is maintained by wall-accretion crystallizing from the rising magma, with columnar olivine growth providing the seismic anisotropy hitherto thought to imply divergent mantle flow from MORs. This model seems to be secured by the remarkable account (Osmaston, 2000b) it gives of many MOR constructional features, notably their straightness and orthogonal segmentation. It also provides much more ridge-push, needed to ensure the subduction of young oceanic plates.

The Semail (Oman) and Bay of Islands (Newfoundland) HEOs each top a sequence of sedimentary slices from a deep-floored basin (Hawasina and Humber Arm respectively), dating back 100Ma or more. Clearly the separative split, of which the sheeted dykes are evidence, occurred within such a basin. Taking this as basis, presuming that the relevant evidence elsewhere has been lost, consider a variant of the MOR model outlined above. The time-thickened plate (deeper crack) would result in an embryo MOR-like volcanic structure which stood high above the adjacent, much older, basin floor (Osmaston, 1980; 1995a). Below it would be a column (5km wide after 50,000 years at 10 cm/yr) of still-partially melted mantle that had been parental to the ridge of crust above. The large topographic contrast (not present at MORs because there is no age-contrast) could, at some point, cause the ridge to burst its side at the level of the magma chamber. This would take the lid off the still-diapiric mantle column below, which would rise rapidly and flow out laterally over the basin floor, carrying with it (or not, as the case might be) some of the crustal ridge just constructed.

Subduction zone magmas owe their distinctive compositions to the presence, during magmagenesis, of water from the subduction interface. In the HEO case (Osmaston, 1980; 1995a), water from the overridden and metamorphosing sole sediments would penetrate this 'mantle laccolith', lowering its solidus and sweating out a sequence of subsequent SSZ-composition magmatism. This would also accomplish the reduction, to dunite layers and pods of residual chromite and dunite, of mafic shear-induced melt segregations within the mantle laccolith, together with the genesis of the wehrlite intrusions that transect the crust-mantle junction.

At this point we now have the HEO sitting on the basin floor forming one side of the split, while the other side continues to recede, creating young oceanic plate. From this, given time, a lot of heat would be transferred laterally into the old lithosphere beneath the HEO, whereas very little transfer could have had time to occur during the genesis and launching of the HEO. This heat transfer would induce density-reducing phase changes (e.g. garnet-to-spinel-to-plagioclase peridotite) within that lithosphere, causing major uplift and sliding of the HEO which, in the process, would acquire a sequence of basin-floor décollement slices below it. These phase changes convert heat into volume increase several tens of times more efficiently than pure thermal expansion, to which geophysicists have hitherto (in ignorance?) confined their attention (Osmaston, 1973; 1999c). The Oman ophiolite confirms a brief sub-aerial exposure at this time; it underwent lateritic weathering, even on the tectonite, before acquiring a sedimentary cover.

This HEO model has many details that accord with observation. One of these is that the walls of the crack would initially be cool, so the mantle intruding it would undergo a lower degree of melting, lining the walls with lherzolite. But it can be shown that after a few hundred metres of rapid separation and wall-accretion the axial temperature profile would stabilize and this effect would vanish. In fact, a few HEOs do show lherzolitic layers near top and bottom of the tectonite, with harzburgite in between. The low degree of melting in the lherzolite zone would have limited the genesis of 'lubricative' melt segregations, often causing it to remain stuck to the walls of the split. The resulting harzburgitic HEOs usually are indeed rich in chromite pods, concentrated near the former lherzolite-harzburgite transition, now the upper zone of the tectonite.

The plate tectonic significance of this model is that the HEO is generated ***and emplaced*** wholly in a plate separation environment. In no way does its emplacement relate to a closure event or the location of a suture. In the Alpide belt, for example, the successive late Jurassic and mid-Cretaceous sets of HEOs signify successive ***additions*** to the Tethyan basin system of Triassic or greater age, whose closure, with such widespread structural consequences, did not occur until the Cenozoic. HEOs do ***not*** represent oceanic crust, but they ***are*** a special variant of the MOR process (as reassessed). The shearing and dislocation caused by the mantle tectonite at the base of the crustal section in HEOs takes place supracrustally with respect to the adjacent basin floor, not subcrustally at an MOR.

Cold-emplaced ophiolites (CEOs), on the other hand, in their role as former oceanic-crusted forearcs, even in the Archaean, do represent oceanic crust, but not necessarily in exactly the form then being generated at MORs. This depends upon the incidence, or not, of sedimentation during construction. Structurally, CEOs become much more deeply involved in the crust (especially in the HP/LT belt situation) than the relatively superficial HEOs. Consequently, going backwards through Earth history, it is much more likely that parts of CEOs will have escaped erosion and remain in the geological record. This seems to accord with observation.

Acknowledgement The ophiolite features referred to herein are recorded in a vast literature by others. Regrettably, space limitation prevents their citation here.

References

Anonymous (1972) Ophiolites. Geotimes, v. 17, pp. 24-25.

Bickle, M.J. and Nisbet, E.G. (1994) Archaean greenstone belts are not oceanic crust. J. Geol., v. 102, pp. 121-138.

Hirth, G. and Kohlstedt, D.L. (1996) Water in the oceanic upper mantle: implication for rheology, melt extraction, and the evolution of the lithosphere. Earth Planet. Sci. Lett., v. 144, pp. 93-108.

Klitgord, K.M., Mudie, J.M., Bischoff, J.L. and Henyey, T.L. (1974) Magnetic anomalies in the northern and central Gulf of California. Geol. Soc. Amer. Bull., v. 85, pp. 815-820.

Osmaston, M.F., 1973. Limited lithosphere separation as a main cause of continental basins, continental growth and epeirogeny. In: Implications of continental drift to the Earth Sciences. Tarling, D. H., and Runcorn, S. K. (Eds.), Academic Press, London. v. 2, pp. 649-674.

Osmaston, M.F. (1980) Model for supracrustal emplacement of ophiolites during plate separation, with implications for nappe systems and the plate kinematics of the Alpide and Caledonide belts. 26th Int. Geol. Congr., Paris. Abstr. v. 1, p. 370.

Osmaston, M.F. (1992) A new model of subducting plate downbend, subduction tectonic erosion, and the large-scale tectonic evolution of convergent margins. 29th Int. Geol. Congr., Kyoto, Japan. Abstr. v. 1, p. 63.

Osmaston, M.F. (1994) A seismicity-compatible new model of subducting plate downbend, basal subduction tectonic erosion (STE) and the large-scale tectonic and seismogenic evolution of convergent margins. IASPEI, 27th Gen. Assy., January 1994, Wellington, New Zealand. Abstr. S8.24.

Osmaston, M.F. (1995a) Two breeds of ophiolite, cold-emplaced (CEO) and hot-emplaced (HEO): does either truly represent what is going on at MORs? International Ophiolite Symposium, September 1995, Pavia, Italy, Abstracts pp. 107-108.

Osmaston, M.F. (1995b) A straightness mechanism for MORs: a new view of ocean plate genesis and evolution. IUGG XXI General Assembly, July 1995, Boulder, Colorado. Abstracts vol. p. A472. [Note. This abstract contains an unfortunate error; the reference to olivine c-axes should read "a-axes".]

Osmaston, M.F. (1997) Pacific-style basal subduction tectonic erosion (STE): essential precursor to construction of the Alps/Carpathians and Apennines. EUG IX, European Union of Geosciences, Strasbourg, France. March 1997. Terra Nova v. 9, Abstr. Suppl. No. 1, p. 341.

Osmaston, M.F. (1999a) Seismic coupling at subduction zones; its mechanical cause and far-reaching geological consequences. IUGG99, Internat. Union Geod. Geophys. XXII Gen. Assy., July 1999, Birmingham, UK. Abstracts p. A.157 (p. A.159 in Abstracts Update CD-ROM).

Osmaston, M.F. (1999b) Phanerozoic subduction and the TTG-magmatic construction of Archaean continental crust. IUGG99, Internat. Union Geod. Geophys. XXII Gen Assy., July 1999, Birmingham, UK. Abstracts p. B.74 (p. B.75 in Abstracts Update CD-ROM).

Osmaston, M.F. (1999c) Some neglected thermophysical properties of mantle materials and their wider implications. IUGG99, Internat. Union Geod. Geophys. XXII Gen Assy., July 1999, Birmingham, UK. Abstracts Update CD-ROM p. A.175.

Osmaston, M.F. (2000a) The magmatic and tectonic construction of Archaean continental crust and why it accelerated. 31st Int. Geol. Congr., August 2000, Rio de Janeiro. Abstracts CD-ROM: Gen. Symp. 9-2.

Osmaston, M.F. (2000b) What goes on beneath MORs? A reassessment. 31st Int. Geol. Congr., August 2000, Rio de Janeiro. Abstracts CD-ROM: General Symposium 4-1.

Peters, Tj., Nicolas, A. and Coleman, R.G. (Eds.) (1991) Ophiolite genesis and evolution of the oceanic lithosphere. Proceedings of the Ophiolite Conference, Muscat, Oman, Jan. 1990. Kluwer Academic Publ., Dordrecht, 903 pp.

Keywords ophiolites; sutures; mid-ocean ridges; plate tectonics; Archaean greenstones.